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Urban development impacts on ecosystems

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Introduction

Once upon a time, when humans existed by hunting and gathering and were themselves prey, there was a “natural” landscape. Since then the Earth’s surface, including the biota, topography, surface and groundwater, has been profoundly and irreversibly altered by the direct and indirect effects of human uses of the land (Sala *et al.* 2000; Vitousek *et al.* 1997; Wilson 1992). By some analyses, the transformation of the surface due to human activities approaches in magnitude the land cover transformations that have occurred during the transitions from glacial to interglacial climate (Meyer and Turner 1994; National Research Council 2001; Ramankutty and Foley 1999).

Changes in land use and land cover can have wide-ranging environmental consequences. These include loss of biodiversity, changes in emissions of trace gases affecting climate change, changes in hydrology and soil degradation (Meyer and Turner 1992). Moreover, changes in land use and land cover can influence vulnerability of people and places to environmental perturbations by, for example, influencing the spread of infectious diseases, interfering with the migration of species and affecting the risk of natural hazards (National Research Council 2001).

The environmental consequences of past and contemporary land uses are drawing significant attention. Deforestation and intensification of agriculture have, for example, received much notice as environmental threats. More recently, urbanization in general, and “urban sprawl” in particular, have been identified as significant environmental stressors (e.g., Kleppel *et al.* 2001; Vernberg *et al.* 1996; Vernberg and Vernberg 2001). No single definition of urban sprawl, or what distinguishes it from more traditional patterns of urbanization, exists (Burchell *et al.* 1998; Johnson 2001). Burchell *et al.* (1998, 2002) identify three essential characteristics implicit in most definitions of urban sprawl: low-density development, leapfrog development and unlimited outward expansion. A more colloquial definition provided by the United States Environmental Protection Agency (EPA) describes urban sprawl as “low density, automobile dependent development beyond the edge of service and employment areas” (US Environmental Protection Agency 2001a:1). This low-density development generally replaces existing acres of farmland, woodland and wetland and automobile-enabled leapfrog development creates seeds around which satellite communities grow. As the landscape becomes increasingly urbanized, the human system becomes more complex and the natural system becomes more simplified (Kleppel and De Voe 2000; Kleppel *et al.* 2001). Moreover, throughout the process of urbanization, ecologically disruptive elements (e.g., impervious surface areas, invasive species) are introduced.

The loss of ecosystem complexity and disruption of ecosystem structure results in a diminished capacity of the landscape to provide environmental services. This environmental degradation is part of what the EPA calls the "hidden debt" of urban sprawl (US Environmental Protection Agency 2001a). In this paper we introduce a conceptual framework for analyzing the environmental consequences of urbanization, provide a brief overview of research that has been conducted on those consequences and suggest a limited set of questions and issues for further research.

Environmental impacts of urban development and sprawl

The environmental impacts of sprawl development differ from those of high-density urban development because the low-density characteristic of sprawl results in a greater overall area being converted to urban use, and because the dispersed nature of sprawl development can create environmental problems above and beyond the impacts attributable to the magnitude of conversion. The predominant characteristics of urban sprawl, low-density and dispersed development, often operate in tandem, but they may have distinctly different effects in terms of environmental impacts. The outward expansion of cities in low-density concentric circles, for instance, may generate a bundle of environmental impacts that differs in composition from that generated by leapfrog development, which not only forms seeds for further sprawl but fragments remaining landscapes and requires a disproportionate amount of additional infrastructure development to support it.

The distinction between the two impacts can be seen to be that of impacts arising from the *magnitude* of conversion versus those arising from the *pattern* of conversion. The magnitude of conversion to urban area in a region can be measured with a simple aggregate indicator of some characteristic of the area converted. Analyzing pattern of conversion, on the other hand, recognizes that environmental impacts may vary with both relative location (i.e., position relative to other land uses) and absolute location, or position within a relevant natural unit such as a watershed or atmospheric inversion basin. Most of the research on the impacts of sprawl has focused on measures of magnitude of sprawl, though theory suggests that certain impacts, particularly those on habitat, may be particularly sensitive to the relative location of development. Because public policy designed to address the pattern of sprawl may look quite different from policy designed to address the magnitude of sprawl, it is important to differentiate between the effects and understand if, and how, they operate separately.

In an attempt to maintain a focus on the distinction between impacts related to magnitude and pattern of sprawl, we categorize impacts of sprawl into four categories: the effects of land conversion, the effects of land use change, the effects of landscape change and induced effects. The category "impacts of land conversion" captures environmental impacts that arise through the actual short-term process of land cover conversion. The remaining categories encompass long-term impacts that can be expected to arise within the system as a result of land use change. These categories address the changes in global and regional indicators of environmental quality that result from after the system has settled into a new state.

Within the remaining categories, the long-terms impacts are categorized as "the effects of land use change" if the impact is primarily generated within the converted parcel itself and is relatively insensitive to the parcel's absolute or relative location. These impacts may be understood and aggregated without reference to location or pattern of conversion. In contrast, "the effects of landscape change" arise precisely because a parcel's relative or absolute location means that its conversion will have a disproportionately larger environmental impact on some class of impacts than the conversion of a parcel of similar size in a different location. Although a sufficiently sophisticated understanding of landscape processes would likely conclude that location is always a significant variable in determining environmental impact, it might also allow us to demonstrate that there will always be some generalizable rules about tradeoffs between amount and location of urban conversion. In anticipation of an understanding of those tradeoffs, we develop a framework based on the distinction between impacts that predominantly arise through magnitude of conversion and those that arise through location of conversion.

The final long-term category of effects is "induced effects," which refer to those environmental effects that can be expected to arise as a result of human behavioral responses to the new landscape structure. Within each category, impacts may also be categorized as "precedent-specific" if the impact in question arises from the conversion of a particular pre-existing land cover, and therefore may be associated with urbanization only in certain cases. Table 7.1 provides an overview of the environmental impacts of urban sprawl.

The effects of land conversion

The effects of land conversion refer to the environmental impacts generated by the process of destruction and reconstruction involved in altering a land parcel's land cover and land use as well as in providing services and access to that parcel. These impacts may be relatively long term, but the window of time within which they are generated is limited to the period of

Table 7.1 Environmental impacts of urban sprawl

Mechanism of impact		*Environmental impacts*	*Research needs*
Conversion processes		Increased erosion	Quantification of impacts
		Trace gas flux	
		Soil compaction	
		Introduction of non-native species	
Impacts of land-cover change	Increase in urban land cover	Increase in impervious surface	Incorporation of location in impact analysis
– degraded water quality			
		– increased flooding	
		– increased variability in stream flow	
		– increased erosion	
		– urban heat island effect	
	Decrease in pre-existing land cover	– loss of wetlands	Quantification of impacts Analysis of regional thresholds of effect
	– loss of habitat area		
	– loss of biomass sinks for atmospheric trace gases		
Impacts of landscape change		– loss of contiguous habitat	Identification of landscape metrics to characterize vulnerability of landscapes
– fragmentation of remaining habitat			

Mechanism of impact		*Environmental impacts*	*Research needs*
		– loss of corridors, migration stops, or dispersability	
		– increased edge	
		– increased presence of non-native or invasive species	Analysis of spatial sensitivity of additional environmental impacts
		– higher species mortality due to increased contact with humans	
Induced effects	Increased vehicle dependence	– air pollution; increased smog and greenhouse gas emissions	Analysis of human behavioral interaction with landscape to explore ways of reducing VMT
		– water pollution; increased deposition of air pollution	
		– water pollution; polluted runoff and road maintenance	
		– increased energy use	
		– stimulated car production	
	Other	– increased risk of abandoned brownfields	
		– possible shift in agricultural production to marginal soils	

actual development. The most widely recognized impacts found in this category are the water and soil quality impacts of road and parcel construction, including increased soil erosion and runoff due to temporary loss of vegetative cover. This effect is exacerbated by the fact that construction inevitably results in soil compaction, which compromises the soil's ability to absorb water (Buol 1994). Grading of parcels for development also encourages invasion and establishment of non-native flora that might have been unable to compete with existing vegetation. The star mustard, an invasive European plant, is speculated to have arrived in Humboldt County, California, on a piece of construction equipment (National Wildlife Federation 2001).

Other precedent-specific effects may also arise as a result of clearing certain types of pre-existing land uses. Cutting a forest for development, for instance, may result in a quick release of the trace gases, including carbon dioxide, sequestered on that parcel. The more long-term impact of such conversion, however, lies in the long-term reduction of global sinks for these gases. This long-lasting effect will be discussed in the next section.

Land conversion's non-specific effects may be the easiest of sprawl's impacts to tackle because they are generated within a finite window of space and time and associated with particular activities. However, while easier to control, these short-term, flow-type impacts may not be the most important. In fact, what differentiates the environmental impacts of sprawl development from other types of development is likely to be found in the other, long-term and landscape-level impacts described below.

The effects of land-cover change

When a parcel of land is converted to urban uses, there are impacts that arise from increasing the urban land-surface cover, and there are impacts that arise from decreasing the amount of whatever cover was pre-existing. Although we limit this category to include only impacts that can be traced directly to the original conversion site, spillover impacts of that conversion may be felt at a much larger spatial scale. Meyer and Turner (1992) argue that altering the land surface and its biotic cover can have regional or global impacts through two different mechanisms. The first is by affecting a regionally or globally fluid system. In this case, impacts from a local conversion site flow to another site via some dispersion system such as air or water. The second mechanism is via aggregation, where enough sites are converted that their aggregate impact can be regionally or globally significant.

There is a substantial literature demonstrating that water quality is impacted by land cover (e.g., Allan *et al.* 1997; Herlihy *et al.* 1998; Jones *et al.* 2001; Roth *et al.* 1996). In urbanizing watersheds, a key water quality concern is the impact of impervious surface areas. A predominant characteristic of urban land surface cover is the prevalence of impervious surfaces. The environmental impacts associated with additional urban land surface cover can in large part be traced back to the resulting increase in impervious surface area. Impervious surfaces are constructed surfaces (i.e., rooftops, sidewalks, roads and parking lots) that are covered by impenetrable materials such as asphalt, cement or concrete and stone, and that therefore repel water and prevent water from infiltrating to the soil (Barnes *et al.* 2001). Transportation-related imperviousness (roads, driveways and parking lots) has been found to account for a greater percentage of impervious cover in many types of communities and may exert a greater hydrological impact as it is often directly linked to storm drain systems (Schueler 1994). Although the rooftop component of impervious surface area is often regulated through traditional density zoning measures, transportation-related imperviousness has been largely neglected by policy (Schueler 1994).

Altering the amount of impervious surface within a watershed has a multitude of environmental impacts; impervious surfaces alter local and regional hydrological cycles and water quality, and produce changes in local energy balances and micro-climates (Barnes *et al.* 2001). In a comprehensive review of the aquatic impacts of impervious cover, the Center for Watershed Protection categorizes those impacts as hydrologic impacts, physical impacts, water quality impacts and biological impacts (Center for Watershed Protection 2003). Impervious cover impacts the hydrologic cycle by altering the volume, pattern and timing of hydrologic flows at various points in the cycle. With an increase in impervious surface area, less precipitation infiltrates into the soil to recharge groundwater and more runs directly off into surface waters. Soil absorbs and stores stormwater, buffers water acidity, delivers nutrients to plant roots and serves as a conduit for groundwater recharge. When the top layer of soil is sealed off, these services are no longer provided. Increased volume of surface water runoff, increased magnitude and frequence of flooding events and decreased stream baseflow during dry periods have all been attributed to increased impervious cover in a watershed (Center for Watershed Protection 2003).

These changes in pattern and timing of water flows also lead to physical changes within the system. Increased stormwater runoff results in higher periodic stream flow, stream channel enlargement and incision, greater stream bank erosion and increased sedimentation in the stream channel (Center for Watershed Protection 2003; Schueler 1994; US Environmental Protection Agency 2001a). The water quality impacts of increased stormwater runoff can also be significant; reduced soil buffering means that urban contaminants (e.g., pesticides, deicers, trace metals and hydrocarbons), acid precipitation and nutrients (e.g., phosphorus and nitrogen) are carried more directly into surface water bodies, leading to higher peak acidity levels, an alteration of natural nutrient cycles, eutrophication and low stream oxygen levels (US Environmental Protection Agency 2001a). Stream temperature has also been found to be correlated to the imperviousness of the contributing watershed (Schueler 1994, citing Galli 1990).

Biological impacts arise from all of these other changes in the aquatic system. Stressors to biological systems that have been attributed to urbanization include the increased stream flow volumes, decreased base flows, increased sediments, loss of stream pools, increases in stream temperature, physical blockages and other changes to stream structure and reductions in water quality (Center for Watershed Protection 2003). These factors combine to significantly reduce habitat quality for stream macroinvertebrates (US Environmental Protection Agency 2001a). Research indicates that aquatic fish and insect communities respond in similar ways to the stream impacts typical of urbanization: egg and larvae survival decreases, total species diversity is reduced and species composition shifts toward more pollution-tolerant species (Center for Watershed Protection 2003; Weaver and Garman 1994). There is also evidence that changes in the hydrologic cycle compromise local wetland areas, with wetland insect community health and wetland plant density declining as impervious cover increases (Center for Watershed Protection 2003). Such wetland communities may rely heavily on groundwater during the dry spells between rains, and the detrimental impacts of urbanization play out through a number of factors such as reduced groundwater recharge, increased fluctuations in wetland water levels and changes in wetland water quality.

Numerous studies have attempted to identify thresholds in the relationship between impervious cover and various types of environmental impacts. A variety of studies indicate that 10 percent impervious cover represents an important threshold for many environmental impacts (Center for Watershed Protection 2003; Schueler 1995). The impervious cover model (ICM) developed by the Center for Watershed Protection assumes that most stream quality indicators decline when impervious cover exceeds 10 percent, and that severe stream degradation is expected when impervious cover exceeds 25 percent (Center for Watershed Protection 2003). Studies of the impacts of impervious surface for the Mid-Atlantic region of the United States indicate that changes in the biotic community in streams emerge when impervious surface is greater than about 3 percent of the watershed area, and that significant degradation of biotic community is observed when impervious surface reaches 10–15 percent or greater (Horner *et al.* 1996; May *et al.* 1997; Schueler and Gali 1992; US Environmental Protection Agency 1999; VanderWilt *et al.* 2003; Wang and Kanehl 2003). According to a study of suburban regions in the Chesapeake Bay area, impervious cover associated with residential development ranges from a mean of 10.6 percent for 2 acre lots to 27.8 percent for quarter acre lots, with townhome and multifamily residential development exceeding 40 percent imperviousness (Capiella and Brown 2001). One could interpret these numbers to mean that greater water quality protection is achievable with low-density development, but such a conclusion ignores the issue of scale: such low-density development spreads development over a much larger area and creates a demand for additional impervious roads to link dispersed communities. When analyzed at the regional or watershed scale, clustered high-density development will leave a larger percentage of the watershed in its natural condition and will decrease overall impervious cover (Kauffman *et al.* 2000).

Urbanization has also been linked to the “heat island effect,” a phenomenon where temperatures within cities are higher than temperatures in surrounding areas. Research suggests that on a summer day, the average temperature in a US city is 3–5 degrees Fahrenheit warmer than surrounding areas, and that this temperature increase may account for 5 to 10 percent of urban peak electric demand (Chen 1994). This effect is due to the combined impacts of removing vegetation and replacing it with dark surfaces such as asphalt roads and dark roofs. The natural cooling effects of vegetative evapotranspiration are eliminated, while the sun-absorbing surfaces of roads and buildings heat up and raise the temperature of the air around them (Pomerantz 1999; Rosenfeld *et al.* 1996). Although this effect has been documented for large urban areas, it is unclear to what extent less concentrated forms of sprawl development generate such an effect.

Precedent-specific environmental impacts of urbanization arise due to the reduction in replaced land cover. The destruction and replacement of parcels bearing biomass has long been recognized to have atmospheric implications arising from changes in the flux and storage capacity for trace gases. When a forest parcel is replaced by an urban parcel, for instance, the region's ability to sequester the greenhouse gas CO_2 is reduced. The same effect would be observed to a lesser extent with the conversion of other natural systems with lower standing biomass. In aggregate, the effects of such conversions on atmospheric CO_2 levels may be substantial. Estimates suggest that the increase in atmospheric CO_2 from land cover change may be 10 to 50 percent of the increase due to industry and fossil fuel burning, which is a far more loudly denounced culprit (Penner 1994). Fluxes in other trace gases, some short-lived and some long-lived, have also been attributed to changes in land use, including the greenhouse gases methane and nitrous oxide, as well as sulfur dioxide and carbon monoxide.

Certain types of habitat have been found to be particularly vulnerable to development. The disappearance and degradation of wetlands in the United States has gained increasing attention over the last decade. It is estimated that between 1780 and 1980, 53 percent of the wetlands found in the lower 48 states, a total of 104 million acres, were lost (Dahl 1990). Net wetland losses have been declining since the 1970s but are still positive; between 1986 and 1997 wetland losses were estimated to average 58,500 acres per year (Dahl 2000). Over that period, development accounted for 51 percent of wetland loss, while loss to agriculture was only 26 percent (Dahl 2000). Between 1982 and 1992, those figures were estimated to be 57 percent and 20 percent, respectively (National Resources Conservation Service 1995). Additionally, policies to reverse wetland loss have focused primarily on wetland acreage rather than quality, and many remaining wetlands are plagued by the water quality issues mentioned above. Such loss and degradation compromises the services that wetlands have traditionally provided: removing nutrients, pesti cides and sediments from surface water; absorbing the impact of storm tides and floods; replenishing groundwater; and providing critical breeding and feeding habitat for birds, fish and other wildlife (National Resources Conservation Service 1995).

When an urban area replaces a wetland, grassland, forest, or agricultural parcel, the viability of species that formerly occupied the parcel or adjacent parcels may be threatened. This impact occurs through two distinct mechanisms. One mechanism is a decline in the absolute amount of habitat available to support that species. The second is the effect of the loss of that parcel on the quality of remaining habitat. The two effects are conceptually quite different, as a small parcel of habitat may be a negligible portion of the total habitat area available, but at the same time it may represent a critical link or buffer such that its loss will have a significant effect on the quality of the habitat remaining in the landscape. This latter effect may far outweigh the importance of the land use change, or habitat loss, on one specific parcel.

Only the first of these two effects should be considered under the category "effects of land cover change." The latter habitat quality effect represents an impact that would fall under the heading "effects of landscape change." In documenting the magnitude of urbanization's impact on species viability, however, this distinction is not often made, as separating the effects would require an intimate understanding of a species' natural history. Therefore, we report evidence on the combined effects of urbanization, and emphasize the importance of recognizing the different mechanisms of impact in future applied research.

Habitat loss has been found to be the primary cause of species decline and endangerment on the mainland United States (Czech *et al.* 2000; Wilcove *et al.* 1998; Wilson 1992). The categories of habitat destruction examined by these studies include agricultural conversion, road construction and maintenance, water development and drainage projects and land conversion for urban and commercial development (Wilcove *et al.* 1998). A list of species pushed to the brink of extinction in large part due to urban sprawl looks like a "Who's Who" of the endangered species act. Of 877 species federally listed as threatened or endangered as of 1994, 275 were attributed primarily to urbanization (Czech *et al.* 2000). In California, one of the most rapidly urbanizing states in the United States, 66 percent of the federally listed threatened or endangered species were attributed to urbanization (National Wildlife Federation 2001), including the San Joaquin kit fox, the Santa Ana mountain lion and the Bay checkerspot butterfly.

As mentioned above, the magnitude of habitat directly lost to urbanization represents only the first wave of impacts that can be expected from land conversion. Urbanization can result in a cascade of secondary effects on habitat quality, including increased fragmentation of remaining habitat, increased exposure to habitat edge effects and introduction of non-native species. These effects are discussed in greater detail below.

The effects of landscape change

If a parcel is removed from a habitat matrix, the remaining habitat will be subjected to external forces that could alter its ability to support the species in question. Urbanization may therefore result in ecological spillovers that alter the landscape's ability to support species in a manner that supercedes loss of a single parcel. We categorize these impacts as effects of landscape change. As mentioned above, urbanization can have land-cover change effects through its reduction in the absolute amount of habitat available, but it can also have wider impacts on the landscape surrounding it that may ultimately more substantially impact species viability. In particular, urbanization results in fragmentation of existing habitat and an accompanying increase in the amount of habitat edge, and increased exposure to edge and non-native species. Habitat fragmentation has often been identified in the literature as a principal threat to a region's biodiversity (Noss and Cooperrider 1995; Wilcox and Murphy 1985).

Habitat fragmentation is produced both by the removal of natural habitat for development, and through the construction of roads, power lines, pipelines, etc., to support the new development. Spillover effects of this new development compromise not only the quality of the remaining habitat but also the accessibility of the remaining habitat. Effects on surrounding habitat quality generally proliferate via the "edge effect." The edge effect refers to the shifts that occur in micro-climate at habitat boundaries; such shifts generate alterations in species composition at habitat boundaries, and often favor exotic species at the expense of native or forest-interior species (Heimlich and Anderson 2001). The encroachment of non-native species at the habitat border results in a further effective loss of habitat for forest-interior species, which may be in direct competition with edge species that have evolved to exploit forest-interior species. Studies of bird populations consistently report correlations between nest predation and brood parasitism and habitat fragmentation (Donovan *et al.* 1997; Robinson *et al.* 1995). The brown-headed cowbird, a brood parasite, has been implicated in the decline of such species as the Kirtland's warbler and the willow flycatcher; the competitive success of this generalist edge species is likely increased by the expansion of its habitat, which brings it into closer proximity to its host species. Even seemingly benign habitat disruptions such as power line corridors can act as a powerful conduit for the invasion of edge and non-native species. Interaction with non-native species has also been found to be a major cause of species endangerment in the United States (Czech *et al.* 2000).

Fragmentation of habitat also limits species' ability to access the habitat that remains to them. Roads form a significant barrier, as many species exhibit an aversion to roads, and some, such as the black bear, cannot cross highways with guard rails (Heimlich and Anderson 2001). Road presence, construction and maintenance have been associated with the endangerment of 94 species nationwide (Czech *et al.* 2000). Roads may also impact species mortality directly; cars and trucks now rank among the main causes of death for pups of the endangered San Joaquin kit fox, and research in Florida suggests that road kills are the primary cause of death for most large mammal species there (Heimlich and Anderson 2001; National Wildlife Federation 2001).

The magnitude of the environmental effects of landscape change can be seen to depend in large part on the interaction that existed between land uses prior to development. In landscapes composed originally of fragmented land uses, the marginal impact of further fragmentation may be minimal. However, in relatively undisturbed landscapes, the impacts generated by even a small amount of disturbance (e.g., through road or bridge building) may be substantial. The impacts of landscape change are therefore highly sensitive to the relative location of development within an existing development matrix.

It is likely that there are other environmental effects whose impacts are determined in large part by location. Unfortunately, there are far more questions about the importance of location than there are answers. Are watersheds more vulnerable to the effects of impervious surfaces on ridges or in the valleys themselves, for instance? It is reasonable to expect that absolute location of land-cover change may play an important role in differentiating water-quality impacts, but we could find little evidence with which to corroborate this theory. The research is currently lacking, but the recent explosive development of simulated landscape modeling is a promising move toward spatially explicit impact analysis.

Induced effects of landscape change

Sprawl-style development induces a pattern of human behavior that generates additional environmental impacts. These impacts, which arise from the landscape occupants' behavioral response to the new landscape form, are categorized as "induced effects of landscape change." Perhaps the most widely denounced aspect of urban sprawl development is the increase in vehicle miles traveled that is believed to accompany the widening distances between locations of residence, work, play and consumption. Between 1980 and 1997, total vehicle miles traveled in the United States rose 63 percent; over that period the annual growth rate in vehicle miles traveled (3.1 percent) was triple that of the population growth rate (1 percent) (US Environmental Protection Agency 2001a).

This disproportionate growth in distance traveled has been attributed by many authors to homeowners' preferences for less dense neighborhoods and workplaces (Downs 1992). In fact, several forces are at work, including the effects of changing demographics and the changing status of women in the workforce (National Personal Transportation Survey 1995). Changes in land use patterns are found to be a significant factor as well, however, with average commute distances increasing by 37 percent between 1983 and 1995, and daily vehicle miles traveled per driver increasing from 28.5 miles to 32.1 miles between 1990 and 1995 (National Personal Transportation Survey 1995, 1999). Due to changes in measurement and methodology, National Personal Transportation Survey (NPTS) results prior to 1990 and post-1990 are not comparable, but the 1990 NPTS survey found that between 1983 and 1990, average per-person trip distances increased by 38 percent and number of trips made per person increased by 25 percent (US Environmental Protection Agency 2001a).

The environmental impacts associated with increased vehicle miles traveled are many and familiar. Exhaust emissions are responsible for increased atmospheric levels of carbon monoxide, sulfur dioxide, particulate matter, hazardous air pollutants, ozone, nitrogen dioxide and lead, among other things. The degradation of air quality arising from exhaust emissions has local health effects as well as global climate effects; the transportation sector is currently responsible for 32 percent of US carbon dioxide emissions, and carbon emissions from transportation are projected to increase by 47.5 percent between 1996 and 2020 (US Environmental Protection Agency 2001a). Vehicle travel also generates the greenhouse gases nitrous oxide and methane (US Environmental Protection Agency 2001a).

Regional water quality is further degraded directly by polluted road runoff and the application of road maintenance materials (salting and de-icing compounds, for instance), as well as indirectly through the deposition of air pollution. Estimates suggest that atmospheric nitrogen may be responsible for 5–50 percent of the total loading to the Chesapeake Bay (with most estimates around 30 percent), and estimates of atmospheric loadings of metals range from 95 percent in the case of lead to 10 percent for cadmium (US Environmental Protection Agency 2001b). Although research has not yet traced these atmospheric pollutants back to their source, it is reasonable to suspect mobile sources as significant contributors. Depending on how far back along the chain of causality one progresses, environmental impacts associated with increased fuel provision, such as oil spills and leaking underground storage tanks, as well as motor vehicle manufacture, could be implicated.

Sprawl development, or rather the ability to engage in sprawl development, may have other consequences that are best considered under the category of "induced" effects. A failure to recognize the full costs of sprawl may result in an increased risk of abandoning rather than mitigating brownfields, for instance. Another charge levied against urban sprawl is that it results in the loss of prime agricultural farmland (American Farmland Trust 1994). Although the highly debated implications for aggregate productivity or food security are not considered in this chapter, if the loss of prime agricultural farmland results eventually in increased reliance on soil types that are less suitable for cultivation, we may experience additional environmental impacts related to intensive use of inputs and increased erosion (Imhoff *et al.* 1998).

Conclusion and future research

Other authors have proposed research agendas to address the costs, environmental and otherwise, of urban sprawl (Burchell *et al.* 2002; Johnson 2001; Pennsylvania Twenty-first Century Environment Commission 1998). We add to those agendas a call for research on the importance of "location, location, location." The spatial aspect of sprawl's impact is important in terms of understanding the magnitude of the biophysical environmental impacts, but it is equally critical because sprawl impacts, and is impacted by, a co-evolving socioeconomic system (see Table 7.1, page 82). Understanding the feedback between systems will be crucial to the design of effective policies for managing sprawl. To what extent do choices for location of residence affect the environmental impact of that development? At what point, and under what conditions, can conversion of that parcel affect landscape-level processes and thresholds? How can that conversion and its aggregate effects be expected to impact back upon the community that made those development choices in the first place? What about impact on other communities that were not involved in the decisions to develop? Does the dynamic of development choices, together with the environmental change that results, lead to an "acceptable" equilibrium between development and environmental quality, or do the system dynamics lead inevitably to degradation and further sprawl? What policies might successfully maintain the system at some intermediate point? The possible questions are, of course, endless; what is critical to future research is the recognition that, while understanding detailed mechanisms of both the biophysical and the socioeconomic mechanisms is important, understanding the interaction between the systems is equally important. We have identified several specific areas of research that will help us move toward that end.

Predicting the ecological consequences of development

- It is clear that urban development alters ecosystems in ways that adversely affect primary productivity, nutrient cycling, resilience, biodiversity and other indicators of aquatic and terrestrial ecosystem structure and function (i.e., health), and a loss of ecosystem services. However, while it is possible to describe changes that have accompanied past development, the scientific basis for predicting the ecological consequences of future development or evaluating the ecological consequences of policies to protect ecosystems is limited. Stressor-response effects are often not well understood, making the consequences of future changes in urban stressor levels uncertain.
- Indicators used to predict the environmental impact of sprawl have traditionally been aggregate measures such as percent of impervious surface or total vehicle miles traveled in a region. Future research should focus in addition on metrics of landscape and development pattern that may be useful in describing how impacted a region is by development as well as predicting how it would respond to future development.

Choosing futures and restructuring patterns of growth

- "Community-based" environmental policy is in vogue, and is appropriate for addressing some local-scale urban environmental externalities. However, much remains to be learned about how to inform citizens of environmental risks, and methods of engaging them in the evaluation and selection of actions.
- Land use controls are typically exercised by local governments, but local political jurisdictions generally do not correspond to the space in which the impacts of local decisions are made. In consequence, decisions that make sense at a local level may have adverse consequences when aggregated. Alternatively, local decisions that are intended to have "good" environmental consequences may be rendered ineffective when environmental outcomes depend on large landscape scale processes that extend beyond the boundaries of the community. How does the scale at which communities make land use decisions affect their pattern of development and therefore the environmental impacts they can expect to see from development? Can coordination of land use decision making be demonstrated to have more benefits for certain types of impacts than for others?
- Communities have a menu of policy instruments for addressing the various issues created by urban development, and for re-structuring growth along preferred paths. However, there is limited economic research to guide policy choices. While the literature on the choice and design of policy instruments for environmental externalities is vast, the context assumed is usually quite limited. The urban environmental externality problem offers multiple stressors emanating from point and non-point sources, affecting a range of ecosystem types over a range of spatial scales, stochastic variations, and both acute and cumulative impacts. This mix alone poses significant theoretical and empirical challenges for the design and evaluation of policy instruments. But the problem is significantly complicated by the fact that the urban environment is one in which a mix of public and private goods are jointly produced, making for a complex web of market and nonmarket interactions that must be addressed in a multiple objective comprehensive design. Community experiences are instructive but may not reveal general lessons. Dynamic simulation experiments using spatially explicit models that couple economic and ecological components offer a method for obtaining robust results.

Landscapes are in constant motion. In our discussion of environmental impacts of sprawl, we have focused on the "global flows" of air and water mentioned above, as well as the animal and plant migration that occurs as species pass through or around matrices of land uses in an attempt to find the resources they need for survival and reproduction. Development moves across the land surface as well, of course, in response to decisions communities and individuals make about appropriate rates and patterns of land conversion. These decisions are made within the existing environmental context, but every time a parcel is converted, the entire environmental landscape adjusts and either new natural pathways of movement of air and water are created, or, in the case of species extinction, the movement itself is stilled. The result is a change in environmental context, perhaps a development response, and eventually a new set of decisions about rates and pattern of land conversion. Effective land-management policies will emerge when we have the information needed to move beyond a myopic approach to land use to anticipate and accommodate the future impacts of today's policies.